Reprinted from *Agronomy Journal*
Vol. 87, No. 4

Aerodynamic Characteristics of Corn as Determined by Energy Balance Techniques

Judy A. Tolk,* Terry A. Howell, Jean L. Steiner, and Daniel R. Krieg

ABSTRACT

Aerodynamic resistance to heat transfer (r_{ah}) needed to calculate sensible heat flux (*H*) used in energy balance modeling can be estimated from momentum aerodynamic resistance with corrections for atmospheric stability. This study compared r_{ah} and *H* modeled by four commonly used resistance methods with r_{ah} and *H* measured indirectly through energy balance techniques. Three momentum aerodynamic parameters were calculated: roughness length, Z_{om}; zero plane displacement, *d*; and friction velocity, U^*. Corn (*Zea mays* L.) was grown on east–west rows (0.75 m wide) in 1989 and 1990 at Bushland, TX, in two contiguous 5-ha fields where two weighing lysimeters were located and micrometeorological measurements were made. Sensible heat flux was indirectly measured as a residual of the energy balance and then used to calculate aerodynamic resistance. Momentum aerodynamic parameters were calculated from near-neutral condition wind-speed profiles using a least squares procedure. The momentum parameter relationships to crop height (CH) were $d = 0.73 \times$ CH ($r^2 = 0.59$) and $Z_{om} = 0.12 \times$ CH ($r^2 = 0.96$). While no r_{ah} model performed well, the best linear fit ($r^2 = 0.75$, $y = 1.08x + 4.2$) between measured (x) and modeled (y) r_{ah} occurred under stable atmospheric conditions; for measured and modeled *H*, the best linear fit ($r^2 = 0.84$, $y = 0.93x + 62.1$) occurred under all atmospheric conditions. Measured r_{ah} in neutral and unstable conditions was not closely associated with wind speed. Performance of a model with a limited stability factor was improved by increasing the magnitude of the factor. These results suggest that r_{ah} models may be sensitive to atmospheric stability and local conditions such as fetch and leaf area.

ENERGY BALANCE MODELING of crops and soils requires estimation of the aerodynamic resistances to heat (r_{ah}), water vapor (r_{av}), and momentum (r_{am}) exchanges between the surface and the atmosphere. The rate of these exchanges is influenced by the magnitude of gradients of the scalars (e.g., temperature, water vapor) and the shape, height, and spacing of the surface elements that control surface roughness and the interaction with wind. The aerodynamic resistances to heat and water vapor fluxes are particularly important in estimating evapotranspiration (ET) rates based on the Penman–Monteith model and the resistance-type energy balance ET model.

The aerodynamic resistances for heat and for water vapor exchanges can be estimated from the momentum aerodynamic resistance based on wind profile characteristics (Thom, 1975) with corrections for atmospheric stability. A surface that is cooler than air will have a vertical transfer of sensible heat toward it, offsetting turbulent transfer due to wind and augmenting aerodynamic resistance. If the surface is warmer than air, the aerodynamic resistance will decrease because of buoyancy. Monteith (1963) suggested that the Richardson number (Ri), a nondimensional parameter proportional to the ratio of energy consumption by buoyancy to energy production by mechanical turbulence, could estimate the changes in aerodynamic resistance due to nonneutral conditions (air temperature not equal to surface temperature). The advantage of Ri over other stability corrections is that it contains only experimentally determined gradients of temperature and wind speed and does not depend directly on sensible heat flux; however, it varies with elevation (Brutsaert, 1982). Because of this height dependence, Ri can be adjusted with an empirically derived constant (n) that depends on how Ri is defined, with the adjustment typically taking the form of $1 + n \times$ Ri. Monteith has variously proposed $n = 10$ (1963) and $n = 5$ (1973). However, as wind speed increases, stability-corrected aerodynamic resistance decreases, regardless of the magnitude of canopy and air temperature differences, and, if the surface becomes aerodynamically smoother, then, at the same value of wind speed and temperature difference, aerodynamic resistance increases (Hatfield el al., 1983; Monteith, 1963). Monteith's (1963) equation for the Richardson number was the basis for later applications by Hatfield et al. (1983, 1984), Mahrt and Ek (1984), and Choudhury (1989). The considerable variation in their adaptation of the stability correction suggests that the successful performance of an aerodynamic resistance equation may be not only crop-specific but in some cases site-specific as well (Raupach and Thom, 1981; Jarvis and McNaughton, 1986).

J.A. Tolk and T.A. Howell, USDA-ARS, P.O. Drawer 10, Bushland, TX; J.L. Steiner, USDA-ARS, P.O. Box 555, Watkinsville, GA; and D.R. Krieg, Dep. of Plant and Soil Science, Texas Tech Univ., Lubbock, TX. Received 22 Nov. 1993. *Corresponding author (Email: !a03lcbushlan@attmail.com).

Published in Agron. J. 87:464–473 (1995).

Abbreviations: DOY, day of year; ET, evapotranspiration; LAI, leaf area index.

Our objectives were to determine momentum aerodynamic characteristics of zero plane displacement, roughness length, and friction velocity for a corn crop from midvegetative through physiological maturity growth stages, and to test and evaluate the performance of the aerodynamic resistance models used by Thom (1975), Hatfield et al. (1983, 1984), Jackson et al. (1987), and Choudhury (1989). The resistance models were evaluated first by comparison of modeled r_{ah} with r_{ah} calculated from sensible heat flux indirectly measured as a residual of the energy balance equation, and then by comparison of modeled sensible heat flux with measured sensible heat flux.

MATERIALS AND METHODS

Agronomy and Instrumentation

Corn (*Zea mays* L.; Pioneer[1] hybrid 3124) was planted on east–west rows (0.75-m wide) in 1989 and 1990 at Bushland, TX, in two contiguous north–south 5-ha fields. A weighing lysimeter, with a 9-m^2 surface area and 2.3-m depth containing a monolithic profile of Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll), was centered in each field. The fields were maintained at or near field capacity, using a lateral move sprinkler system. Mass changes due to water loss were measured using a lever scale with a mechanical advantage of 100:1 and counterbalanced so that ≈ 10% of the lysimeter mass was measured by a 22.7-kg load cell providing an ET accuracy of 0.05 mm of water. Mean plant density in 1989 was 5.9 plants m^{-2}; in 1990 it was 5.7 plants m^{-2}.

Each lysimeter was instrumented to measure net radiation (REBS Model Q5.5, Radiation Energy Balance Systems, Renton, WA) and canopy temperature (Everest Model 4003 infrared thermometer with a 15° field of view and a nominal precision of 0.1 °C, Everest Interscience, Fullerton, CA). The infrared thermometer was mounted obliquely at 1 m above the crop surface viewing 60° from nadir to the southwest, a view similar to that recommended by Huband and Monteith (1986), and viewed an area of the crop canopy of ≈ 0.1 m^2 southwest of the sensor. Corrections (<0.5 °C) to the surface temperatures (Jackson, 1988) were made to account for the reflection of atmospheric longwave radiation emitted by the surroundings to the sensor and for the emissivity of the surface.

Wind speed (cup anemometer Model 014A, Met One, Grants Pass, OR), air temperature, and vapor pressure were measured in close proximity to each lysimeter at 1.0, 1.3, 1.8, and 2.8 m above the crop surface. Wind speed data < 0.5 m s^{-1} were excluded. Air temperature and vapor pressure were determined from aspirated wet-bulb and dry-bulb psychrometers similar to the design of Lourence and Pruitt (1969). Soil heat flux at each lysimeter was measured by four soil heat flux plates (REBS model HFT-1) at the 0.05-m depth (two in furrows and two in beds). The soil heat flux was corrected for the heat storage in the 0- to 0.05-m depth as determined from soil temperature in that layer and the heat capacities of the soil constituents of minerals, organic matter, and water content. Water content was estimated as a daily value from biweekly 0.2-m neutron probe measurements (Hydroprobe model 503 DR, CPN Co., Martinez, CA), assuming a linear decline between wetting events and measurements.

The micrometeorological and lysimeter data were recorded at each lysimeter with separate dataloggers (Model CR-7X, Campbell Scientific, Logan, UT). The lysimeter load cell data were measured at 2-s intervals, with 5-min means and standard deviations recorded. The micrometeorological sensors were measured at 6-s intervals and recorded as 15-min means. The 5-min lysimeter data and the 15-min micrometeorological data were composited into 30-min mean values.

Calculation of d, Z_{om}, and U^*

The adiabatic mean wind profile can be described as a logarithmic function of height:

$$U_Z = (U^*/k)\ \ln[(Z - d)/Z_{om}]\,, \qquad [1]$$

where U_Z is wind speed (m s^{-1}) at reference height Z (m); U^*, commonly known as friction velocity (m s^{-1}), is $(\tau/\rho)^{1/2}$, where τ is the momentum flux and ρ is the density of air; k is von Karman's constant (0.41); d is zero plane displacement (m); and Z_{om} is roughness length (m). For the 1990 growing season from midvegetative [DOY 170, LAI = 0.8] through physiological maturity growth stages (DOY 260, LAI = 3.6, with a maximum LAI of 5.9 at DOY 207), 290 cases of neutral to near-neutral condition wind-speed profiles from both lysimeters were selected for aerodynamic parameter analysis by MathCAD (version 2.5, MathSoft, Cambridge, MA) following a procedure suggested by Howell (1990). This procedure involved determination of the profile parameters (d, Z_{om}, U^*) that minimize the sum of squares between the measured wind speeds and the estimated wind speeds of a profile given as

$$\mathrm{SSE} = \frac{\Sigma_{i=1}^{N}\ \{U_i - (U^*/k)\ \ln[(Z_i - d)/Z_{om}]^2\}}{N - 1}\,, \qquad [2]$$

subject to N constraints (one for each measurement level i) as

$$U_i = (U^*/k)\ \ln[(Z_i - d)/Z_{om}]\,. \qquad [3]$$

The simplified Richardson number (Ri) (Monteith, 1963; Kustas et al., 1989) used to determine neutral to near-neutral conditions ($-0.008 \le \mathrm{Ri} \le 0.008$) and for stability corrections is

$$\mathrm{Ri} = [g(T_a - T_c)\ (Z - d)]/(T_{av}\ U_Z^2)\,, \qquad [4]$$

where g is the acceleration of gravity (9.8 m s^{-2}), T_a the air temperature (K), T_c the plant canopy temperature (K), T_{av} is the average temperature taken as $[(T_a + T_c)/2]$, and U_Z is as defined for Eq. [1]. The range of $(T_a - T_c)$ values in the neutral to near-neutral conditions evaluated was $-1 \le (T_a - T_c) \le 1$.

Evaluation of Aerodynamic Resistance Equations

The energy balance of a surface (Rosenberg et al., 1983) has been given as

$$R_n + \lambda E + H + G = 0\,, \qquad [5]$$

where R_n is net radiation, λE is latent heat flux, H is sensible heat flux, and G is soil heat flux, all in W m^{-2}, with each term positive toward the crop. If R_n, λE, and G are measured, H can be calculated as the residual of Eq. [5]:

$$H = -(\lambda E + R_n + G)\,. \qquad [6]$$

Sensible heat flux can also be defined as:

$$H = \rho\ C_p\ (T_a - T_c)/r_{ah}\,, \qquad [7]$$

where ρ is the density (kg m^{-3}) and C_p is the specific heat (J kg^{-1} K^{-1}) of air at constant pressure.

Equations Used in the Analysis

The exchange of heat, momentum, and water vapor between a surface and the atmosphere can be derived from the known relationships between fluxes and potential differences, such as temperature, wind speed, or humidity. The rate of the exchange

[1] Mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by the USDA-ARS.

flux is a function of the gradients of the scalars and the resistance to their movement that is governed by the aerodynamic properties of the system. The aerodynamic resistance to momentum transport in the absence of buoyancy effects (neutral stability) follows directly from Eq. [1] (Thom, 1975):

$$r_{am} = \ln[(Z_i - d)/Z_{om}]^2 / k^2 U_Z . \quad [8]$$

Under diabatic conditions, Eq. [8] must be corrected. We have followed the example of Monteith (1963) and Hatfield et al. (1983, 1984) in using the Richardson number for stability correction, then assuming similarity in transport of heat and momentum, yielding

$$r_{ah} = r_{am} (1 + 5\mathrm{Ri}) . \quad [9]$$

By definition (Thom, 1975), the aerodynamic resistance to heat transfer can also be written as

$$r_{ah} = \rho\, C_p\, (T_a - T_c) / H . \quad [10]$$

Hatfield et al. (1983, 1984) used Eq. [9] to estimate r_{ah}, which they then used to calculate H, using Eq. [7]. This was used with Eq. [5] to estimate ET. They found ET calculated by their model to be well correlated with lysimeter measurements of cotton (*Gossypium* spp.), grain sorghum [*Sorghum bicolor* (L.) Moench], soybean [*Glycine max* (L.) Merr.], alfalfa (*Medicago sativa* L.), and tomato (*Lycopersicon esculentum* Mill.) at various locations throughout the USA.

Choudhury (1989) and Choudhury et al. (1986), similarly evaluating a surface energy balance ET model but over wheat (*Triticum aestivum* L.), recognized that the source-sink surfaces for momentum exchange ($d + Z_{om}$) and for heat exchange ($d + Z_{oh}$, where Z_{oh} is the roughness length in m for heat) were different. Their exact analytic equation for r_{ah} under stable conditions is

$$r_{ah} = \frac{\{\ln[(Z - d)/Z_{om}] - \psi^*\}\,\{\ln[(Z - d)/Z_{oh}] - \psi^*\}}{k^2\, U_Z}, \quad [11]$$

where $Z_{oh} = Z_{om}/10$, and ψ^* is a stability function defined as

$$\psi^* = [b - (b^2 - 4ac)^{1/2}] / 2a , \quad [12]$$

$$a = 1 - \eta , \quad [13]$$

$$b = \ln[(Z - d)/Z_{oh}] - 2\eta\{\ln[(Z - d)/Z_{om}]\} , \quad [14]$$

$$c = -\eta\, \{\ln[(Z - d)/Z_{om}]^2 , \quad [15]$$

and

$$\eta = 5\,\mathrm{Ri} . \quad [16]$$

Their equation for unstable and neutral conditions is

$$r_{ah} = \frac{\ln[(Z - d)/Z_{om}]\ \ln[(Z - d)/Z_{oh}]}{k^2 U_Z\, (1 - \eta)^{3/4}} . \quad [17]$$

Based on turbulent transport coefficients given by Louis (1979) with constraints determined largely from experimental data, Mahrt and Ek (1984) formulated equations for r_{ah} under stable and unstable conditions. These equations were adapted by Jackson et al. (1987) for the stable case as

$$r_{ah} = \frac{\{\ln[(Z - d + Z_{om})/Z_{om}]^2\ (1 + 15\mathrm{Ri})\ (1 + 5\mathrm{Ri})^{1/2}\}}{k^2 U_Z}, \quad [18]$$

and for the unstable and neutral cases as

$$r_{ah} = \left\{ \ln\left[\frac{Z - d + Z_{om}}{Z_{om}}\right]^2 (k^2\, U_z)^{-1} \right\} \times \left\{ 1 - \left[\frac{15\mathrm{Ri}}{1 + C(-\mathrm{Ri})^{1/2}}\right] \right\}^{-1}, \quad [19]$$

where

$$C = \frac{75k^2\, [(Z - d + Z_{om})/Z_{om}]^{1/2}}{\{\ln[(Z - d + Z_{om})/Z_{om}]\}^2}, \quad [20]$$

Jackson et al. (1987) reported good agreement between calculated ET and ET measured by Bowen ratio techniques on cotton, wheat, and alfalfa in Arizona with wind speeds averaging 2.5 m s^{-1}.

We also evaluated the effect of ignoring stability effects by using Eq. [8] to estimate r_{am} and again assuming similarity between momentum and heat transport. This equation represents the bulk aerodynamic resistance to the transfer of momentum from height Z in the atmospheric flow over an extensive plant community. The magnitude of r_{am} is an inverse function of wind speed and surface roughness, which does not include a separate roughness length for heat.

Procedures for Testing

First, sensible heat flux was calculated as a residual of the energy balance equation using Eq. [6]. We felt this indirect measurement was a valid approach because a linear regression of Bowen ratio energy balance measurements on Bushland lysim-

Table 1. Mean and standard error (SE) of wind speed at height Z (U_Z), the air–canopy temperature difference ($T_a - T_c$), Richardson number (Ri), and measured and modeled aerodynamic resistance to heat transfer (r_{ah}) and sensible heat flux (H) for 30-min intervals from Day of Year 210 to 249 in 1989, used in the aerodynamic analysis for stable, neutral, unstable, and all atmospheric stability conditions.

Parameter	Stable		Neutral		Unstable		All	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
n	62		126		48		236	
U_Z (m s^{-1})	2.4	0.08	3.8	0.08	3.0	0.09	3.3	0.06
$T_a - T_c$ (K)	1.6	0.06	0.38	0.03	−2.1	0.08	0.2	0.09
Ri	0.026	0.002	0.002	0.000	−0.025	0.003	0.003	0.001
Modeled r_{ah} (s m^{-1})								
Thom (Eq. [8])	13.1	0.40	8.4	0.20	10.8	0.39	10.2	0.21
Hatfield (Eq. [9])	15.0	0.58	8.6	0.21	9.2	0.19	10.4	0.26
Choudhury (Eq. [11], [17])	30.0	1.17	17.2	0.42	19.8	0.52	21.1	0.53
Jackson (Eq. [18], [19])	22.1	1.22	9.6	0.24	10.0	0.25	13.0	0.50
Measured r_{ah} (s m^{-1})	16.6	0.98	4.7	0.33	23.4	1.41	11.6	0.66
Modeled H (W m^{-2})								
Thom (Eq. [8])	135.9	6.50	51.4	4.89	−210.0	7.91	20.4	8.68
Hatfield (Eq. [9])	121.1	5.95	50.5	4.85	−243.0	10.02	9.3	9.28
Choudhury (Eq. [11], [17])	60.7	2.96	25.1	2.40	−113.1	4.30	6.3	4.41
Jackson (Eq. [18], [19])	87.7	4.95	44.4	4.34	−223.3	8.59	1.3	8.14
Measured H (W m^{-2})	116.5	6.28	101.2	6.60	−109.0	7.63	62.5	7.00

Table 2. Mean and standard error (SE) of wind speed at height Z (U_Z), the air–canopy temperature difference ($T_a - T_c$), Richardson number (Ri), and measured and modeled aerodynamic resistance to heat transfer (r_{ah}) and sensible heat flux (H) for 30-min intervals from Day of Year 210 to 249 in 1990, used in the aerodynamic analysis for stable, neutral, unstable, and all atmospheric stability conditions.

Parameter	Stable		Neutral		Unstable		All	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
n	76		100		7		183	
U_Z (m s^{-1})	2.6	0.08	3.6	0.10	2.6	0.25	3.2	0.07
$T_a - T_c$ (K)	1.8	0.04	−0.13	0.05	−1.4	0.10	0.61	0.08
Ri	0.026	0.002	−0.000	0.000	−0.025	0.009	0.010	0.001
Modeled r_{ah} (s m^{-1})								
Thom (Eq. [8])	10.6	0.31	7.8	0.26	11.1	1.41	9.1	0.22
Hatfield (Eq. [9])	12.1	0.44	7.8	0.26	9.4	0.61	9.7	0.28
Choudhury (Eq. [11], [17])	24.9	0.91	16.4	0.55	21.0	1.96	20.1	0.57
Jackson (Eq. [18], [19])	18.2	0.94	8.8	0.31	10.5	0.93	12.8	0.54
Measured r_{ah} (s m^{-1})	21.0	0.87	4.7	0.39	7.5	0.92	11.6	0.72
Modeled H (W m^{-2})								
Thom (Eq. [8])	186.9	7.20	−24.7	7.83	−132.6	7.00	59.1	9.66
Hatfield (Eq. [9])	167.6	7.04	−25.9	7.82	−151.9	3.92	49.6	9.17
Choudhury (Eq. [11], [17])	81.5	3.41	−12.2	3.73	−68.5	2.24	24.6	4.40
Jackson (Eq. [18], [19])	119.6	5.91	−25.0	6.92	−136.5	4.12	30.8	7.31
Measured H (W m^{-2})	103.2	6.20	−70.1	11.00	−202.0	17.49	−3.2	9.51

eter energy balance measurements yielded a slope of 1.01, an r^2 of 0.95, and a standard error of estimate equal to 36 W m^{-2} (Bausch and Bernard, 1992). Aerodynamic resistance was then calculated from the residually determined sensible heat flux using Eq. [10]. While we recognize that H or r_{ah} calculated from energy balance techniques are not actual measured values, we shall refer to them as measured in this discussion so that they can be easily distinguished from modeled values.

Next, modeled aerodynamic resistance was calculated using Eq. [8], [9] and [11] to [20] and then modeled H was calculated using Eq. [7]. Measured and modeled r_{ah} and H were statistically compared using SAS Procedure General Linear Models (SAS Institute, Cary, NC) in stable [$(T_a - T_c) > 1$, Ri > 0.008], neutral [$-1 \leq (T_a - T_c) \leq 1$, $-0.008 \leq$ Ri ≤ 0.008], unstable [$(T_a - T_c) < 1$, Ri < -0.008], and all (combined) atmospheric stability conditions. In the Results and the Discussion sections, the resistance models and their associated equations presented in this text will be referred to as the Thom (Eq. [8]), Hatfield (Eq. [9]), Choudhury (Eq. [11]–[17]), and Jackson (Eq. [18]–[20]) equations (or models).

Tables 1 and 2 present the mean and standard error values for the input data, as well as measured and modeled r_{ah} and H used in the aerodynamic resistance analysis of the 1989 and 1990 data sets. For both years, the 40-d period (DOY 210–249) used for the analysis represents a period of maximum ground cover from anthesis through grain fill, with a stable crop height (CH) of 2.3 m in 1989 and 2.8 m in 1990. The environmental conditions were moderate, with afternoon air temperatures ranging from 23 to 30°C, wind speeds from 2 to 5.6 m s^{-1}, vapor pressure deficits from 1.2 to 2.4 kPa, midday maximum net radiation near 700 W m^{-2}, and minimum soil heat flux near −30 W m^{-2}. Values of $(T_a - T_c)$ ranged from −3.8 to 4.0°C in 1989, and from −1.8 to 2.8°C in 1990. For both years, $(T_a - T_c)$ values were typically limited to less than ±2.5°C, and wind speeds ranged from 1.1 to 5.6 m s^{-1}, with ≈55% of the wind speeds > 3 m s^{-1}. The crop surface was rough [$(Z - d)/Z_{om} < 9.0$, with reference height Z at 1.8 m above the crop surface], with a maximum measured r_{ah} of 42.5 s m^{-1} in 1989 and 60.4 s m^{-1} in 1990. Maximum sensible heat flux toward the canopy occurred late in the afternoon, and maximum sensible heat flux away from the canopy occurred during midmorning.

Wind speed data used in the analysis were restricted to the dominant south–southwesterly wind direction blowing across east–west oriented rows. In 1989, data were taken from the north lysimeter, with a minimum fetch of 250 m and maximum fetch of 330 m. Due to a faulty infrared thermometer at the north lysimeter, the 1990 data were taken from the south lysimeter allowing minimum and maximum fetches of 105 m and 145 m, respectively. Reference wind speed and wet- and dry-bulb temperatures were measured at 1.8 m above the crop surface. Due to limitations in the measurement accuracy of T_c and ET (and consequently λE), all data from periods in which ET rates were < 0.06 mm h^{-1} and for which H and $(T_a - T_c)$ values differed in sign were eliminated from the analysis. Time periods during rainfall events and during and after irrigations when the instrumentation was within the canopy were also excluded.

RESULTS

Momentum Aerodynamic Resistance Characteristics

The MathCAD analysis reached solutions for d, Z_{om}, and U^* in 90 cases out of 290 cases. A regression of d on crop height (CH, in m) (Fig. 1) yielded a slope of 0.73 ($r^2 = 0.59$), a result similar to reported slopes of 0.75 (Jacobs and van Boxel, 1988), of 0.76 (Thom et al., 1975) and of 0.72 (Abtew et al., 1989), but 16% higher than the slope of 0.63 reported by Monteith (1973) and 49% higher than the slope of 0.49 reported by Lemon and Wright (1969). According to Thom et al. (1975), low ratios of d/CH may be the result of atmospheric instability, with a slope of 0.75 being "a possibly more realistic value." The regres-

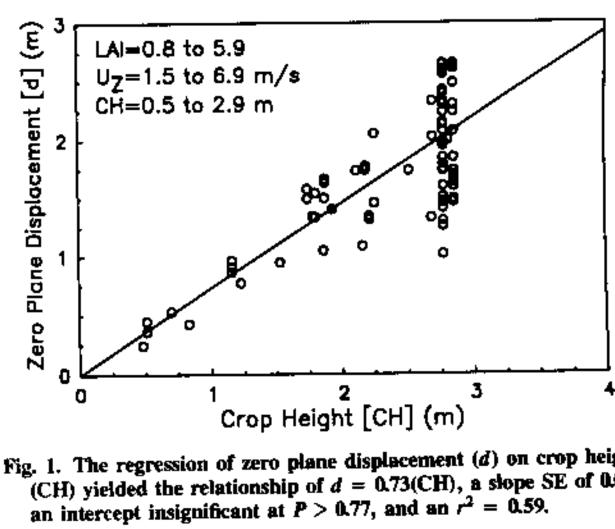

Fig. 1. The regression of zero plane displacement (d) on crop height (CH) yielded the relationship of d = 0.73(CH), a slope SE of 0.02, an intercept insignificant at $P > 0.77$, and an $r^2 = 0.59$.

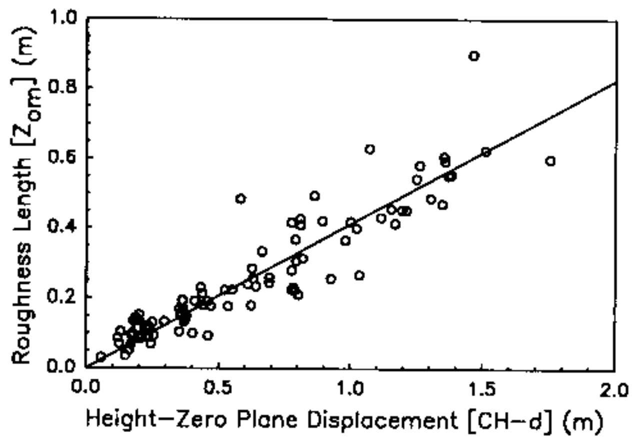

Fig. 2. The regression of roughness length (Z_{om}) on crop height minus zero plane displacement (CH − d) yielded the relationship of Z_{om} = 0.41(CH − d), a slope SE of 0.01, an intercept insignificant at $P >$ 0.29, and an r^2 = 0.96.

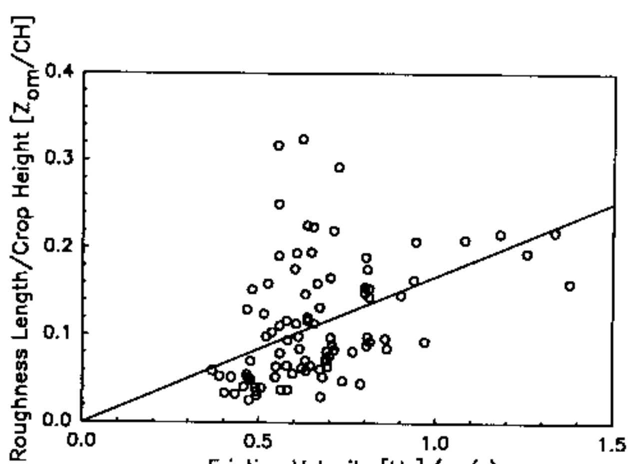

Fig. 4. The regression of the ratio of roughness length to crop height (Z_{om}/CH) on friction velocity (U^*) yielded the relationship Z_{om}/CH = 0.14(U^*), a slope SE of 0.01, an intercept insignificant at $P > 0.43$, and an r^2 = 0.16.

sion of Z_{om} on (CH − d) (Fig. 2) yielded a slope of 0.41 (or 0.12 × CH), which is close to the 0.13 × CH value reported by Monteith (1973) and the 0.14 × CH value of Tanner and Pelton (1960) but almost twice that of 0.06 × CH given by Jacobs and van Boxel (1988) for corn and three times that of 0.04 × CH estimated by Abtew et al. (1989) for various crops.

The dependence of d and Z_{om} on U^* is shown in Fig. 3 and 4, respectively. A decrease in d/CH was observed with increasing friction velocity, as reported by Azevedo and Verma (1986) for sorghum and by Rauner (1976) for deciduous trees. The vertical line of data points at CH ≈ 2.8 m in Fig. 1 also represents this relationship. Unlike data reported by Azevedo and Verma (1986) for sorghum, however, Z_{om} increased, rather than decreased, with increasing friction velocity. This behavior follows that predicted by Monteith (1973) for larger and more rigid leaves over a wide range of wind speeds, which he ascribed to a substantial lowering of the canopy height due to turbulent eddies. Similar behavior in corn (lowered d, increased Z_{om}) was summarized by Uchijima (1976). The low r^2 and high standard error may reflect additional interactions between friction velocity and canopy structure due to the changes in LAI.

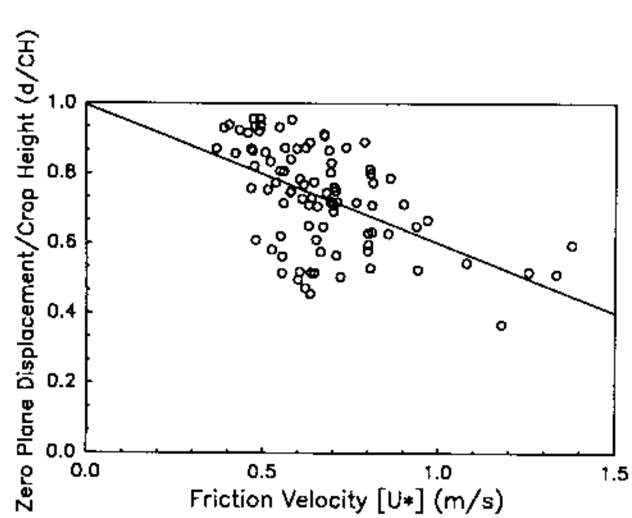

Fig. 3. The regression of the ratio of zero plane displacement to crop height (d/CH) on friction velocity (U^*) yielded the relationship of d/CH = 1.0 − 0.40(U^*) with the SE of the slope 0.07 and of the intercept 0.05, and an r^2 = 0.28.

Aerodynamic Resistance Equations

Stable Atmospheric Conditions

For both years, the models performed best in stable atmospheric conditions, producing in general the highest coefficients of determination and lowest standard errors of estimate. In 1989 (Table 3), r_{ah} modeled by the Choudhury and Jackson equations produced slopes that nearly paralleled that of measured r_{ah}, but the intercepts resulted in an overprediction of r_{ah} (Fig. 5) and an underprediction of H (Fig. 6) as compared with measured values. Mean r_{ah} and H modeled by the Thom and Hatfield equations (Table 1) were similar to measured values, as shown by the clustering of modeled r_{ah} near to the 1:1 line (Fig. 5). In 1990, the slopes and intercepts for modeled r_{ah} of all equations were lower than in 1989 (Table 4). This improved the performance of the Choudhury and Jackson models in predicting r_{ah} and H, while the Thom and Hatfield models underpredicted r_{ah} and overpredicted H. In both years, r_{ah} modeled by Thom and Hatfield equations showed limited response to measured r_{ah} increases.

Neutral, Unstable, and All Atmospheric Stability Conditions

In both years, no model performed well in neutral or in unstable atmospheric conditions, especially in predicting measured r_{ah} (Tables 4 and 5). Across all atmospheric stability conditions (combined) in both years (Table 6), r_{ah} modeled by Thom, Hatfield, and Jackson equations overestimated measured r_{ah} at values < 10 s m^{-1} and underestimated measured r_{ah} at higher values (Fig. 7). The Choudhury model overestimated measured r_{ah} at values ≤ 30 s m^{-1}. While the slopes of modeled H in 1989 and 1990 were similar, the negative intercepts of 1989 led to an underprediction of H by all equations (Fig. 8). In

Table 3. Summary of regression analyses comparing modeled to measured aerodynamic resistance to heat transfer (r_{ah}) and sensible heat flux (H) (Eq. [10], [6]) for Day of Year 210 to 249 under stable atmospheric conditions ($T_a - T_c > 1$, Ri > 0.008) in 1989 (n = 62) and 1990 (n = 76).†

Model	r_{ah} analysis				H analysis			
	r^2	a	b	$s_{y \cdot x}$‡	r^2	a	b	$s_{y \cdot x}$
Thom (Eq. [8])								
1989	0.55**	8.1**	0.31**	2.1	0.44**	56.2**	0.68**	38.7
1990	0.44**	5.6**	0.23**	2.0	0.67**	88.9**	0.95**	36.4
Hatfield (Eq. [9])								
1989	0.66**	7.1**	0.48**	2.7	0.54**	40.2**	0.69**	32.1
1990	0.44**	5.0**	0.34**	2.9	0.65**	73.1**	0.92**	36.4
Choudhury (Eq. [11])								
1989	0.67**	13.7**	0.98**	5.3	0.54**	20.1**	0.35**	15.9
1990	0.44**	10.3**	0.69**	6.0	0.65**	35.6**	0.44**	17.6
Jackson (Eq. [18])								
1989	0.75**	4.2**	1.08**	4.9	0.61**	16.2*	0.61**	24.7
1990	0.42**	3.5	0.70**	6.2	0.59**	44.0**	0.73**	33.2

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† The regression equation takes the form: r_{ah} (modeled) = a + b (measured).
‡ $s_{y \cdot x}$ = standard error of the estimate.

1990, the Thom and Hatfield models overpredicted H while the Choudhury and Jackson models in general underpredicted H at values > 100 W m^{-2}. The Thom model returned the best estimate of H.

DISCUSSION

Ottoni et al. (1992) also evaluated the Hatfield, Choudhury, and Jackson models in estimating H under stable

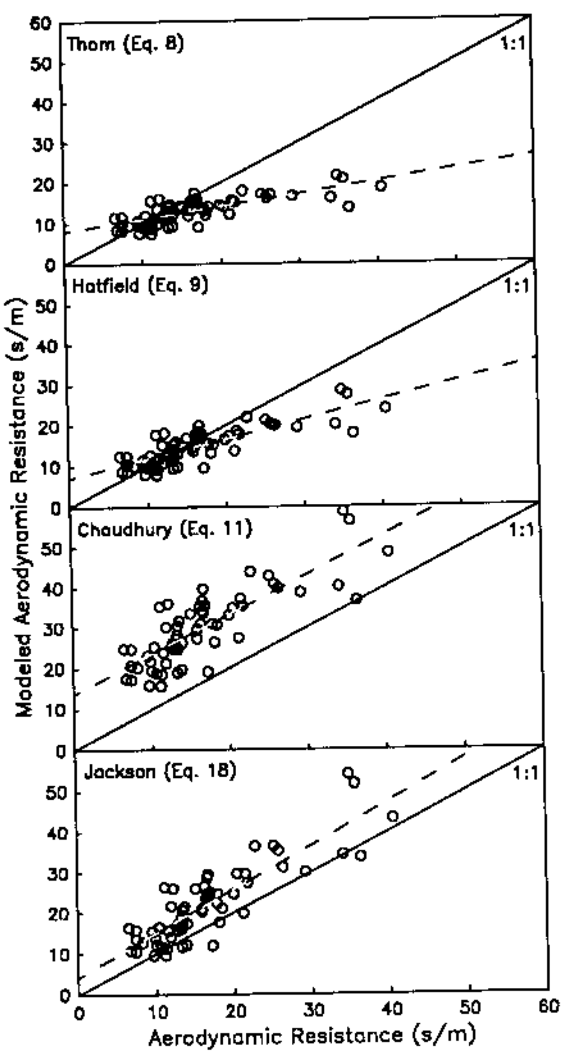

Fig. 5. The regressions of modeled aerodynamic resistance on indirectly measured aerodynamic resistance under stable atmospheric conditions in 1989.

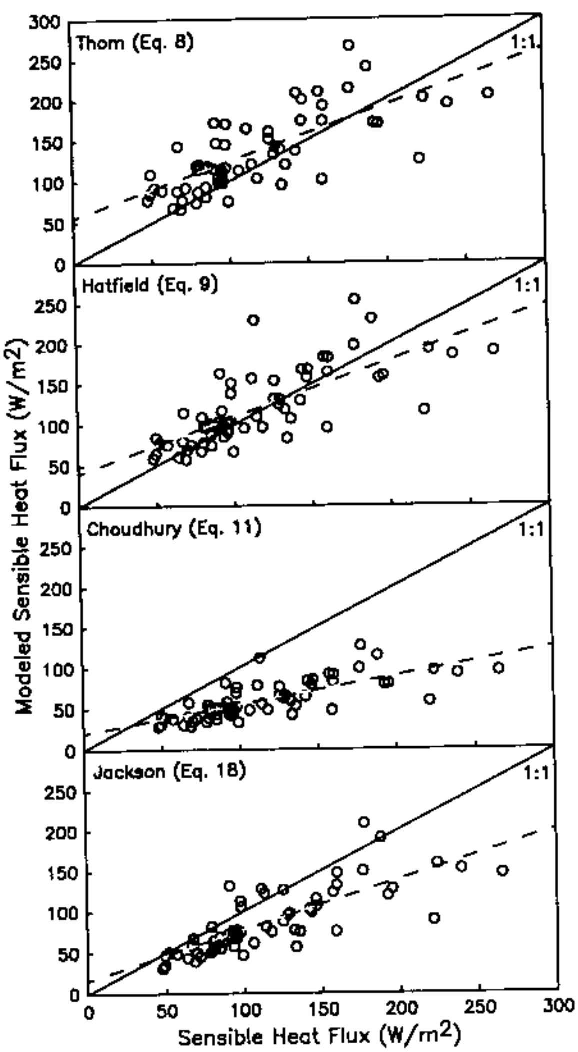

Fig. 6. The regressions of modeled sensible heat flux on indirectly measured sensible heat flux under stable atmospheric conditions in 1989.

Table 4. Summary of regression analyses comparing modeled to measured aerodynamic resistance to heat transfer (r_{ah}) and sensible heat flux (H) (Eq. [10], [6]) for Day of Year 210 to 249 under neutral atmospheric conditions ($-1 \leq T_a - T_c \leq 1$, $-0.008 \leq Ri \leq 0.008$) in 1989 ($n$ = 126) and 1990 (n = 100).†

	r_{ah} analysis				H analysis			
Model	r^2	a	b	$s_{y \cdot x}$‡	r^2	a	b	$s_{y \cdot x}$
Thom (Eq. [8])								
1989	0.04*	9.0**	−0.13*	2.2	0.36**	9.7	0.40**	44.0
1990	0.01	8.2**	−0.07	2.6	0.75**	18.7**	0.62**	39.0
Hatfield (Eq. [9])								
1989	0.04*	9.1**	−0.13*	2.3	0.36**	9.2	0.40**	43.6
1990	0.01	8.1**	−0.05	2.6	0.75**	17.4**	0.62**	39.0
Choudhury (Eq. [17])								
1989	0.04*	18.4**	−0.26*	4.6	0.36**	4.6	0.20**	21.6
1990	0.01	17.0**	−0.12	5.5	0.75**	8.4**	0.29**	18.6
Jackson (Eq. [19])								
1989	0.03	10.2**	−0.13	2.7	0.36**	7.5	0.36**	39.1
1990	0.00	8.9**	−0.01	3.1	0.75**	13.3**	0.55**	34.5

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† The regression equation takes the form r_{ah} (modeled) = a + b (measured).
‡ $s_{y \cdot x}$ = standard error of the estimate.

atmospheric conditions over turfgrass. Their test conditions included ($T_a - T_c$) differences averaging 5°C, wind speeds generally < 3 m s^{-1}, and measured $H \leq 75$ W m^{-2}. As in our analysis, they found that the Hatfield model overpredicted H (underpredicted r_{ah} due to the large intercepts) by ≈ 15% at lower sensible heat fluxes (<100 W m^{-2}). However, they showed fairly good agreement between measured and modeled H for the Choudhury model ($y = 0.83x - 6.7$, $r^2 = 0.74$, $s_{y \cdot x} = 6.2$ W m^{-2}) and the Jackson model ($y = 0.89x - 6.3$, $r^2 = 0.75$, $s_{y \cdot x} = 6.4$ W m^{-2}). They suggested that the Hatfield model might perform better under neutral conditions.

The performance of all equations in our analysis may have been limited by the reduced impact of the stability correction due to wind speed. The Richardson number was very small when wind speed exceeded 3 m s^{-1} under stable, neutral, and unstable atmospheric conditions (Fig. 9), which occurred > 50% of the time. In a sensitivity analysis, Ottoni et al. (1992) found that an increase of 0.2 m s^{-1} in wind speed changed mean H as much as 17%. The lack of association between measured r_{ah} and wind speed (Fig. 10) in neutral and unstable atmospheric conditions also limited the performance of the models. Even in stable atmospheric conditions, measured r_{ah} was strongly associated with wind speed only at values < 3 m s^{-1}. Neutral atmospheric conditions, which typically occurred in high wind speeds with low r_{ah} (Fig. 9), yielded no significant linear relationships (Table 4), which can be seen in the fairly flat associations between measured and modeled r_{ah} values < 10 s m^{-1} (Fig. 7). The considerable scatter in the 1989 data is the result of a higher number of unstable data points (20% in 1989 vs. 4% in 1990) in the analysis. In 1989, the mean measured r_{ah} in unstable atmospheric conditions was 40% higher than mean measured r_{ah} in stable conditions (Table 1), which does not follow theory. Many of the flat data points of r_{ah} modeled by the Jackson (Fig. 7) equations are unstable data points.

Sensitivity Analysis

We examined the sensitivity of the Choudhury and Hatfield models to changes in model inputs for the 1989 and 1990 stable atmospheric data sets. The Choudhury model requires separate roughness lengths for heat and momentum. Thom and Oliver (1977) suggested that the error incurred by assuming Z_{oh} equaled Z_{om} may not be significant, because of wake diffusion effects described by Thom et al. (1975) that may augment effective Z_{oh}. They emphasized that it is more important not to overestimate

Table 5. Summary of regression analyses comparing modeled to measured aerodynamic resistance to heat transfer (r_{ah}) and sensible heat flux (H) (Eq. [10], [6]) for Day of Year 210 to 249 under unstable atmospheric conditions ($T_a - T_c < -1$, Ri < −0.008) in 1989 (n = 48) and 1990 (n = 7).†

	r_{ah} analysis				H analysis			
Model	r^2	a	b	$s_{y \cdot x}$‡	r^2	a	b	$s_{y \cdot x}$
Thom (Eq. [8])								
1989	0.00	10.7**	0.00	2.7	0.24**	−154.2**	0.51**	48.2
1990	0.32	4.6	0.87	3.4	0.00	−137.7*	−0.03	20.2
Hatfield (Eq. [9])								
1989	0.00	9.0**	0.01	1.3	0.45**	−147.1**	0.88**	52.1
1990	0.25	6.9*	0.33	1.5	0.22	−173.1**	−0.11	10.0
Choudhury (Eq. [17])								
1989	0.00	19.6**	0.01	3.7	0.36**	−76.3**	0.34**	24.1
1990	0.30	12.3	1.17	4.8	0.05	−74.3**	−0.03	6.3
Jackson (Eq. [19])								
1989	0.00	9.9**	0.01	1.8	0.38**	−147.8**	0.69**	47.4
1990	0.30	6.4	0.56	2.3	0.06	−148.2**	−0.06	11.6

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† The regression equation takes the form: r_{ah} (modeled) = a + b (measured).
‡ $s_{y \cdot x}$ = standard error of the estimate.

Table 6. Summary of regression analyses comparing modeled to measured aerodynamic resistance to heat transfer (r_{ah}) and sensible heat flux (H) (Eq. [8], [6]) for Day of Year 210 to 249 under all atmospheric stability conditions in 1989 (n = 236) and 1990 (n = 183).†

	r_{ah} analysis				H analysis			
Model	r^2	a	b	$s_{y \cdot x}$‡	r^2	a	b	$s_{y \cdot x}$
Thom (Eq. [8])								
1989	0.22**	8.4**	0.15**	2.9	0.71**	−43.8**	1.01**	71.6
1990	0.28**	7.2**	0.16**	2.6	0.84**	62.1**	0.93**	51.9
Hatfield (Eq. [9])								
1989	0.17**	8.5*	0.17**	3.7	0.74**	−60.7**	1.10**	72.8
1990	0.43**	6.7**	0.25**	2.9	0.85**	52.5**	0.89**	48.2
Choudhury (Eq. [11], [17])								
1989	0.20**	16.9**	0.36**	7.3	0.74**	−26.8**	0.52**	34.9
1990	0.40**	14.3**	0.50**	6.0	0.85**	25.9**	0.43**	23.3
Jackson (Eq. [18], [19])								
1989	0.19**	9.2**	0.33**	6.9	0.75**	−60.5**	0.97**	62.6
1990	0.54**	6.3**	0.56**	4.9	0.85**	33.0**	0.71**	38.2

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† The regression equation takes the form: r_{ah} (modeled) = a + b (measured).
‡ $s_{y \cdot x}$ = standard error of the estimate.

Z_{om}. Thom et al. (1975) suggested that on an aerodynamically rough surface, additional mixing by turbulent eddies behind individual roughness elements created temperature and water vapor profiles relatively less steep than the wind-speed profiles. To evaluate this concept, we tested the Choudhury model by setting Z_{oh} equal to Z_{om} and increased the roughness length to Z_{om} = 0.13 × CH. In 1989, these assumptions produced a best-fit modeled r_{ah}

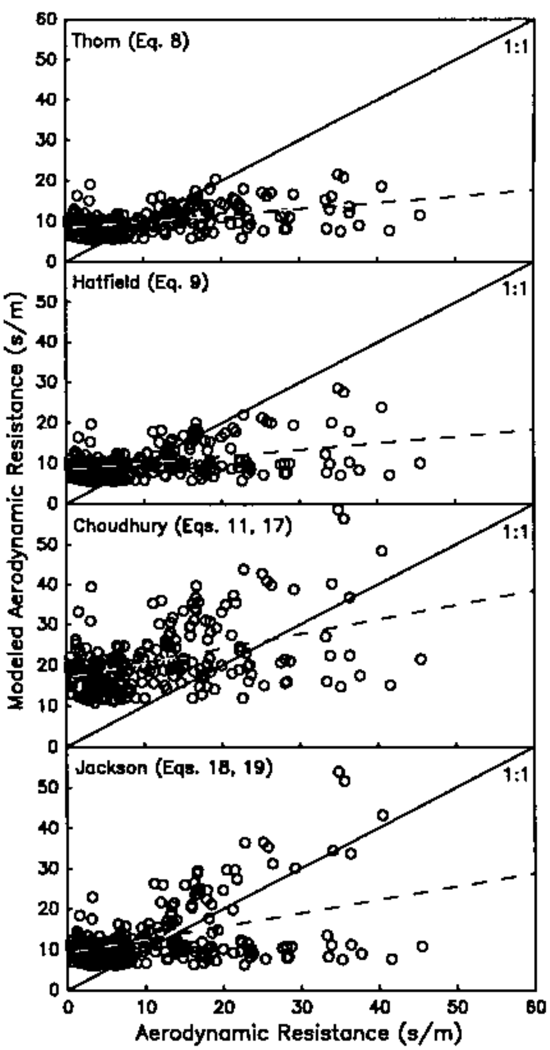

Fig. 7. The regressions of modeled aerodynamic resistance on indirectly measured aerodynamic resistance under all atmospheric conditions in 1989.

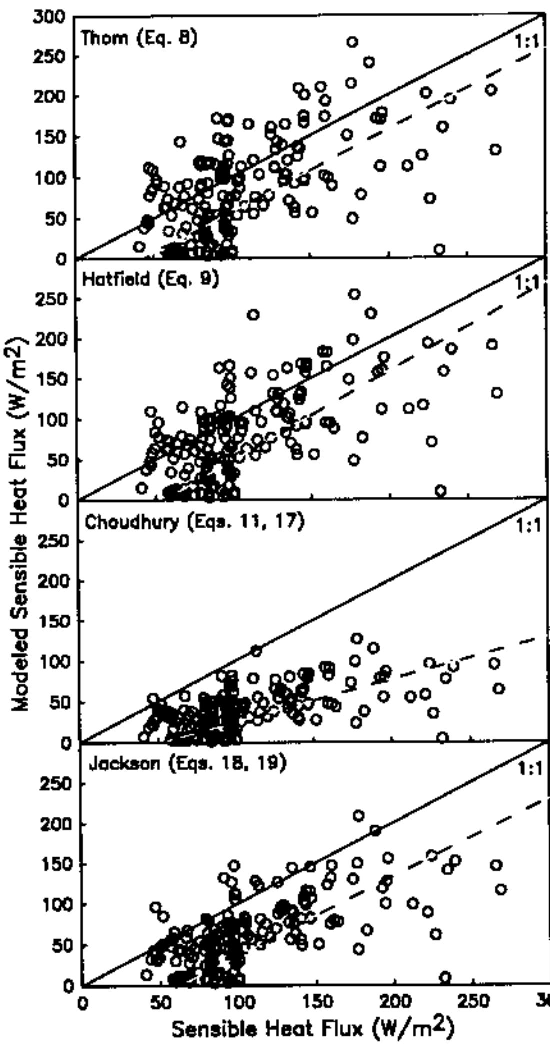

Fig. 8. The regressions of modeled sensible heat flux on indirectly measured sensible heat flux under all atmospheric conditions in 1989.

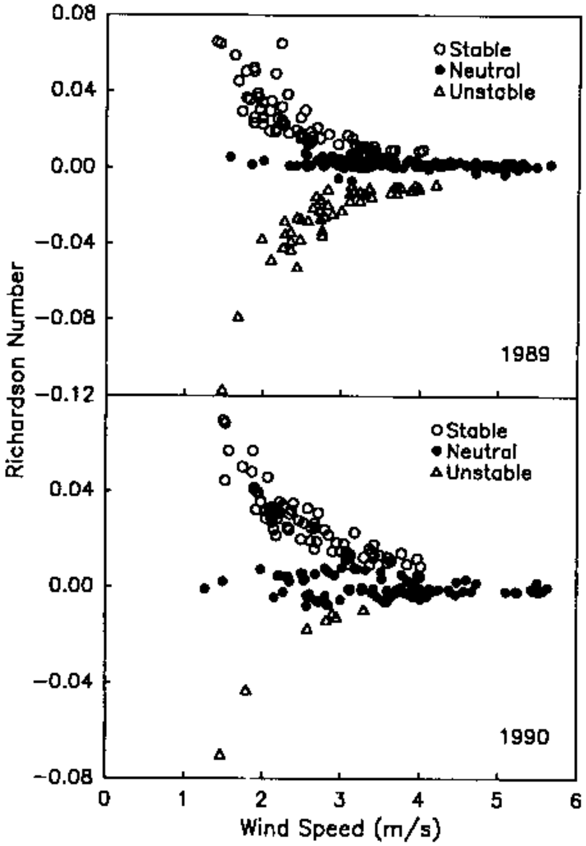

Fig. 9. The response of the Richardson number to wind speed and atmospheric stability.

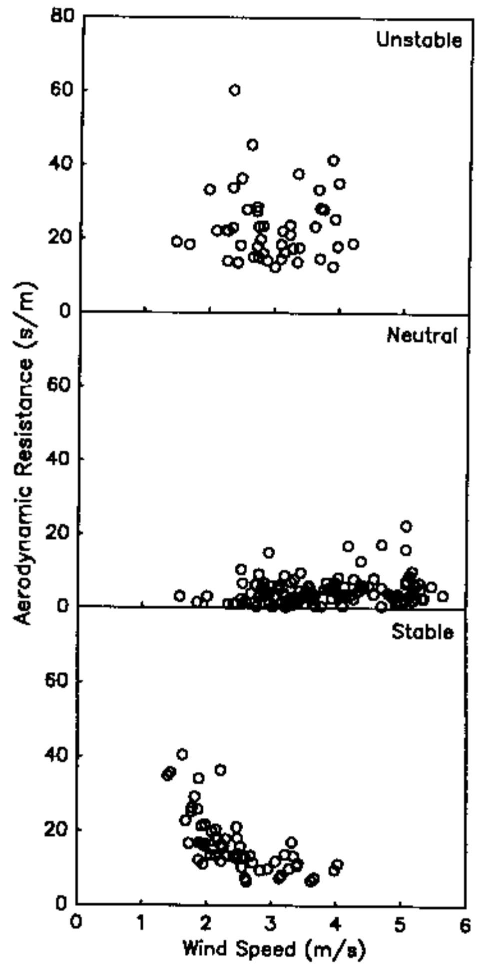

Fig. 10. The response of measured aerodynamic resistance to wind speed under stable, neutral, and unstable atmospheric conditions in 1989.

slope of 0.80, an intercept of 2.6 s m^{-1}, an r^2 of 0.76, an $s_{y \cdot x}$ of 3.5 s m^{-1}, and a mean of 15.9 s m^{-1}; and a modeled H slope of 0.83, an intercept of 24.8 W m^{-2}, an r^2 of 0.62, an $s_{y \cdot x}$ of 32.5 W m^{-2}, and a mean of 121.1 W m^{-2}. The reduction in the modeled r_{ah} intercept by 11.1 s m^{-1} more than doubled the modeled H slope and increased the coefficient of determinations by 13 to 15% as compared with the 1989 model evaluation data (Table 3). In 1990, model input changes did reduce the modeled r_{ah} intercept, but did not improve the linear relation of modeled H to measured H (data not shown).

The Hatfield model utilizes the Richardson number adjustment for stability given by Monteith (1963) {e.g., in Eq. [9], $(1 + n \times \mathrm{Ri})$, where $n = 5$}. Following the suggestion by Monteith (1963) that n be determined empirically, n was raised iteratively until a best fit was reached. The roughness length was also increased to $Z_{om} = 0.13 \times$ CH. In 1989, the best-fit empirical constant was $n = 24$, which produced a modeled r_{ah} slope of 0.99, an intercept of 2.8 s m^{-1}, an r^2 of 0.75, an $s_{y \cdot x}$ of 4.4 s m^{-1}, and a mean of 19.2 s m^{-1}. As compared with regression parameters presented in Table 3, the larger empirical constant more than doubled the slope, reduced the intercept 4.3 s m^{-1}, and increased the r^2 by 9% and the $s_{y \cdot x}$ by 1.7 s m^{-1}. In predicting H, the model slope and r^2 increased 6%, the intercept was negligible, and the $s_{y \cdot x}$ declined 2 W m^{-2}. In 1990, the assumption that $n = 24$ did improve the model performance, but not as extensively as in 1989. Increasing n to 50 returned a best-fit modeled r_{ah} slope of 1.07, an intercept of −0.27 s m^{-1}, an r^2 of 0.41, an $s_{y \cdot x}$ of 9.7 s m^{-1}, and a mean of 22.1 s m^{-1}; and a modeled H slope of 0.72, an intercept of 33.1 W m^{-2}, an r^2 of 0.51, an $s_{y \cdot x}$ of 38.6 W m^{-2}, and a mean of 107.5 W m^{-2}. While modeled r_{ah} and H linear regression parameters from the modified equation did not improve as compared with model parameters presented in Table 3, mean modeled r_{ah} and H values were within 5% of measured r_{ah} and H (Table 2).

The test conditions in 1989 and 1990 differed in height, fetch, and leaf area. In 1989, the crop height was 2.3 m, the fetch exceeded the recommended 100:1 relationship, and leaf area index (LAI) ranged from 4.7 to 3.7. In 1990, crop height was 2.8 m, the fetch was less than the 100:1 relationship, and LAI ranged from 5.7 to 4.4. In 1989 stable atmospheric conditions (Fig. 5 and 6), the models of Choudhury (Eq. [11]) and Jackson (Eq. [18]) with more extensive stability corrections overpredicted measured r_{ah} and underpredicted measured H. The models of Thom (Eq. [8]) and Hatfield (Eq. [9]) with limited to no stability corrections returned r_{ah} and H values nearer to the 1:1 line. All equations achieved a better fit with an increase in roughness length, as did the Choudhury model with the assumption that Z_{oh} equaled Z_{om}. This suggests that, although the fetch was adequate and the crop height shorter, the crop was aerodynamically rougher and, thus, more mixing occurred.

In 1990, the models of Thom and Hatfield underestimated measured r_{ah}, with the equations of Choudhury and Jackson modeling r_{ah} nearer the 1:1 line. The linear fit of modeled to measured r_{ah} and H for the Choudhury equation was reduced when Z_{oh} was assumed to equal Z_{om}. To achieve the best fit for the Hatfield model, the empirical constant for Ri had to be increased to $n = 50$. This suggests a less aerodynamically rough surface that allowed the development of an added resistance to heat transfer.

CONCLUSIONS

This analysis was performed to identify a method for calculating aerodynamic resistance with locally derived aerodynamic parameters that could be used to estimate sensible heat flux, an important component of the energy balance equation (Eq. [5]). The equations performed best in stable atmospheric conditions, when r_{ah} was clearly associated with wind speeds < 3 m s^{-1} (Fig. 10). No equation did well in neutral and unstable atmospheric conditions, because of the lack of association between measured r_{ah} and wind speed. The performance of the Hatfield model could be enhanced by increasing the empirically derived constant n that weights the impact of the Richardson number (i.e., $1 + n \times \mathrm{Ri}$, where $n = 24$ in 1989 and $n = 50$ in 1990). However, this constant was unique for each year and may be a function of height, fetch, wind direction, and/or leaf area. Assuming that Z_{oh} equaled Z_{om} enhanced the performance of Choudhury model in 1989, but did not in 1990, which may mean that other factors such as leaf area may also be important. The Choudhury model, while not returning the best linear fit as the modified equations, seemed less sensitive to differences in test conditions between years. These results indicate that r_{ah} models may be sensitive to atmospheric stability and their performance can be influenced by local conditions such as leaf area, crop height, or fetch.

REFERENCES

Abtew, W., J.S. Gregory, and J. Borrelli. 1989. Wind profile: Estimation of displacement height and aerodynamic roughness. Trans. ASAE 32:521-527.

Azevedo, P.V., and S.B. Verma. 1986. Aerodynamic characteristics of grain sorghum. Agric. For. Meteorol. 38:193-204.

Bausch, W.C., and T.M. Bernard. 1992. Spatial averaging Bowen ratio system: Description and lysimeter comparison. Trans. ASAE 35: 121-128.

Brutsaert, W. 1982. Evaporation into the atmosphere. D. Reidel Publ. Co., Boston.

Choudhury, B.J. 1989. Estimating evaporation and carbon assimilation using infrared temperature data: Vistas in modeling. p. 628-690. *In* G. Asrar (ed.) Theory and application of optical remote sensing. John Wiley & Sons, New York.

Choudhury, B.J., R.J. Reginato, and S.B. Idso. 1986. An analysis of infrared temperature observations over wheat and calculation of latent heat flux. Agric. For. Meteorol. 37:75-88.

Hatfield, J.L., A. Perrier, and R.D. Jackson. 1983. Estimation of evapotranspiration at one time-of-day using remotely sensed surface temperatures. Agric. Water Manage. 7:341-350.

Hatfield, J.L., R.J. Reginato, and S.B. Idso. 1984. Evaluation of canopy temperature-evapotranspiration models over various crops. Agric. For. Meteorol. 32:41-53.

Howell, T.A. 1990. Wind profile parameter estimation using MathCAD. Agron. J. 82(5):1027-1030.

Huband, N.D.S., and J.L. Monteith. 1986. Radiative surface temperature and energy balance of a wheat canopy: I. A comparison of radiative and aerodynamic canopy temperature. Boundary Layer Meteorol. 36:1-17.

Jackson, R.D. 1988. Surface temperature and the surface energy balance. p. 133-153. *In* W.L. Steffen and O.T. Denmead (ed.) Flow and transport in the natural environment: Advances and applications. Springer-Verlag, Berlin.

Jackson, R.D., M.S. Moran, L.W. Gay, and L.H. Raymond. 1987. Evaluating evaporation from field crops using airborne radiometry and ground-based meteorological data. Irrig. Sci. 8:81-90.

Jacobs, A.F.G., and J.J. van Boxel. 1988. Changes of the displacement height and roughness length of maize during a growing season. Agric. For. Meteorol. 42:53-62.

Jarvis, P.G., and K.G. McNaughton. 1986. Stomatal control of transpiration: Scaling up from leaf to region. Adv. Ecol. Res. 15:1-49.

Kustas, W.P., R.D. Jackson, and G. Assam. 1989. Estimating surface energy-balance components from remotely sensed data. p. 604-627. *In* G. Asrar (ed.) Theory and applications of optical remote sensing. John Wiley & Sons, New York.

Lemon, E.R., and J.L. Wright. 1969. Photosynthesis under field conditions: XA. Assessing sources and sinks of carbon dioxide in a corn (*Zea mays* L.) crop using a momentum balance approach. Agron. J. 61:405-411.

Louis, J.F. 1979. A parametric model of vertical eddy fluxes in the atmosphere. Boundary Layer Meteorol. 17:187-202.

Lourence, F.J., and W.O. Pruitt. 1969. A psychrometer system for micrometeorology profile determination. J. Appl. Meteorol. 8:492-498.

Mahrt, L., and M. Ek. 1984. The influence of atmospheric stability on potential evapotranspiration. J. Clim. Appl. Meteorol. 23:222-234.

Monteith, J.L. 1963. Gas exchange in plant communities. p. 95-112. *In* L.T. Evans (ed.) Environmental control of plant growth. Academic Press, New York.

Monteith, J.L. 1973. Principles of environmental physics. Edward Arnold, London.

Ottoni, T.B., A.D. Matthias, A.F. Guerra, and D.C. Slack. 1992. Comparison of three resistance methods for estimating heat flux under stable conditions. Agric. For. Meteorol. 58:1-18.

Rauner, J.L. 1976. Deciduous forests. p. 241-264. *In* J.L. Monteith (ed.) Vegetation and the atmosphere. Vol. 2. Case studies. Academic Press, London.

Raupach, M.R., and A.S. Thom. 1981. Turbulence in and above plant canopies. Annu. Rev. Fluid Mech. 13:97-129.

Rosenberg, N.J., B.L. Blad, and S.B. Verma. 1983. Microclimate: The biological environment. John Wiley & Sons, New York.

Tanner, C.B., and W.L. Pelton. 1960. Potential evapotranspiration estimated by the approximate energy balance method of Penman. J. Geophys. Res. 65:3391-3413.

Thom, A.S. 1975. Momentum, mass, and heat exchange of plant communities. p. 57-109. *In* J.L. Monteith (ed.) Vegetation and the atmosphere. Vol. 1. Principles. Academic Press, New York.

Thom, A.S., and H.R. Oliver. 1977. On Penman's equation for estimating regional evaporation. Q. J. R. Meteorol. Soc. 103:345-357.

Thom, A.S., H.R. Oliver, and J.H.C. Gash. 1975. Comparison of aerodynamic and energy balance budget estimates of fluxes over a pine forest. Q. J. R. Meteorol. Soc. 101:95-105.

Uchijima, Z. 1976. Maize and rice. p. 33-64. *In* J.L. Monteith (ed.) Vegetation and the atmosphere. Vol. 2. Case studies. Academic Press, New York.